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STELLAR PARALLAXES

BY ADRIAAN VAN MAANEN

The present paper aims to deal with the development and the present state of the "trigonometrical" or "directly determined" parallaxes.

The term "parallax" in a general way means the change of apparent direction of an object arising from a change in the position of the observer; in particular the parallax of a star is the angle between the directions in which the star appears from two points separated from each other by the mean distance of the Earth from the Sun.

It is clear that when the Earth moves around the Sun every star must seem to describe a little orbit in the sky which in shape is the exact representation of the Earth's orbit as seen from that star; the size of this apparent orbit will be smaller the farther away the star is; on the other hand, from the size of this orbit we can deduce the distance of the star.

Aristarchus of Samos, who observed at Alexandria 280-264 B. C., is the first person known to maintain that the Earth was moving around the Sun; from the lack of a detectable annual shift of the stars he deduced the relative smallness of the Earth's orbit as compared with the distances of the stars. After him Hipparchus and Ptolemaeus, the leading astronomers of that time, readopted the geocentric theory, and this viewpoint was not abandoned until Copernicus laid the foundations of the heliocentric theory (1506-1512). During that long interval of time, therefore, the only way of determining the distances of the stars was thru the use of a base-line on the Earth itself. Altho we know now that such a base-line is too small to detect the parallax of our nearest stars, even with the most modern instruments, several unsuccessful attempts were made. When Copernicus published his heliocentric theory the necessity of proving the annual shift of the stars, due to the Earth's motion around the Sun, became more necessary than ever. Assiduous attempts were made, not so much from the desire to determine the distances of the stars, as to prove that the Copernican theory was the true one. It was still supposed that all the stars were at the same distance from us and the values derived for their common parallax range from 6″ to 611″. This idea of the common distance had adherents as late as 1642, notwithstanding the fact that Tycho

Brahe had as early as 1597 suggested that the stars are at different distances, and Kepler had confirmed in 1606 the idea that the brighter stars are the nearer. From this time on we find many astronomers of such renown as Tycho Brahe, Hooke, Cassini, and Flamsteed engaged in trying to find the displacements of individual stars during the year, in order to show whether the theory of Copernicus were true. This, however, was proved to be so, not by the detection of any parallax, but by Bradley's famous discovery of the aberration of light. Samuel Molyneux, who wanted to check all that had been said before about the proper motions and parallaxes of the stars, ordered a sector of 24 feet, which he installed at Kew near London. He determined with this instrument the zenith distance of γ *Draconis* on December 3, 5, 11, and 12, 1725; the observations agreed well. Bradley, who then happened to be at Kew, made another observation on December 17 and found that γ *Draconis* passed a little to the south as compared with its position before; on December 20 the star was still farther south. At first these differences were attributed to errors in the instrument, but a continued series of measures showed that the star kept on moving south until March, 1726, when its position was 20″ south of that in December; in September the star was 39″ north of its position in March, and in December it was again in the identical position as in the same month in 1725. The remarkable part was that the observations did not agree in phase with the effect due to a parallactic shift, and it was therefore necessary to look for another explanation. It was finally ascribed to the progressive transmission of light combined with the annual motion of the Earth in its orbit, a phenomenon known as the aberration of light. However, while Bradley's observations failed to discover the parallax of the stars, they proved the Earth's motion around the Sun (1729), and when continued brought to light another phenomenon known as the nutation (1748).

All these measures had been made by determining one of the co-ordinates, mostly zenith distances, of some chosen star; in this way any change in the instruments will be reflected in the result by its full amount; it was for this reason that William Herschel in 1782 discussed the advantages of a differential method for determining stellar parallaxes. The great advantage of determining the relative shift of two stars apparently near together is that instrumental or seasonal changes will vitiate the relative distances only in a differential way; the drawback is that we do not get the absolute parallax of any star, but the difference of the parallaxes of the two stars. In order to find such pairs as seemed desirable for the work Herschel began his famous catalogs of double stars. From the large number of stars found close together compared with the number of such coincidences to be expected in case the stars were evenly distributed in space, Michell came to the conclusion that most of them must be physically connected (1783). This deduction based on the calculus of probability was confirmed in 1803, when William Herschel proved that some of his double stars, without showing any shift due to parallax, appeared to have a common proper motion and even an orbital motion of one star around another.

If, therefore, all the work done thus far had not solved the original problem, it had brought to light three remarkable astronomical phenomena, viz., aberration, nutation, and the existence of physical double stars. Moreover, in the attempt to make the observations more and more accurate, the instruments had been materially improved. New and more accurate instruments were designed and it is due in great measure to the skill of some of the best instrument makers, that the original problem finally was solved; in particular, Fraunhofer's construction of the heliometer proved to be a great help in this kind of work. This is an equatorial telescope whose object glass is divided along a diameter into two halves which can slide along each other, each half forming a separate image of any star at which the telescope is pointed. If there are two stars in proximity, the image of one star made by one-half of the object glass can be brought into coincidence with that of the other star made by the other half. The amount that the two halves of the objective must be moved with respect to one another affords us the angular distance of the two stars. To Bessel, who used this instrument, is ordinarily given the credit of having first determined the parallax of a star with such certainty as to place the result beyond doubt. And yet it is extremely difficult to say who really first determined the parallax of any star. At about the same time three observers, viz., Bessel, W. Struve, and Henderson, made known their results of the parallaxes of three different stars, determined in three different ways.

Their results are summarized in the following table:

Author	Star	Observed	Published	Parallax	P. E.	Method
Bessel	61 Cygni	1837–1838	1838	+0″.314	±0″.014	Diff. Heliometer
W. Struve	α Lyrae	1835–1836	1837	+0 .125	±0 .055	Diff. Micrometer
Henderson	α Centauri	1832–1833	1839	+1 .16	±0 .11	Abs. Mer. Circle

The best modern results give for these stars parallaxes of +0″.311, +0″.090, and +0″.759, respectively; the close agreement, especially in the case of Bessel and Struve, shows the remarkable skill of these early observers, not only in making their observations but also in handling their material. The work of Bessel and Struve indicated the great advantage of the differential method, and the absolute method was with very few exceptions abandoned.

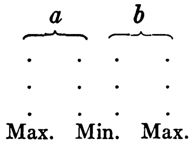
Ever since Bessel's observations of 61 *Cygni* the heliometer has continued to be used for parallax work, as it has two great advantages over the ordinary equatorial telescope combined with a micrometer; first, much more distant comparison stars can be used, and second, the stars under observation can be made of the same apparent magnitude by placing a wire gauze screen over the segment of the object-glass which forms the image of the brighter star. In the hands of Gill at the Cape of Good Hope, and later in those of Peter at Leipsic and Elkin and his collaborators at Yale, it has done excellent work; the last named observatory has now published parallaxes of about 250 stars.

In later years the meridian-circle has come into use again, but in a differential way. The first extended series is due to Kapteyn, who from 1885 to 1887 applied the differential method to 15 stars by means of the meridian-circle at the Leiden Observatory; his conclusion was that this instrument, with which the work can be done in less time than with the heliometer, is able to yield the same accuracy. His method has been employed more recently, especially by Flint at Madison, Jost and Abetti at Heidelberg, and Jewdokimov at Charkow.

The most important change in parallax determinations in recent years has come from the introduction of photography into astronomy. The credit for the first determination goes to Pritchard at

Oxford, who published his results for the parallax of 61 *Cygni* in 1886. The advantage of this method is the large number and the faintness of comparison stars that can be used. It is true that at the beginning a large number of plates had to be taken to derive a reliable result; Pritchard, for instance, used about 100 exposures for the derivation of each of his 21 parallaxes of the stars of the second magnitude, and such a large number of plates necessitated a considerable time spent at the instrument and a correspondingly large amount at the measuring machine and in the reductions. With the improvement of the photographic plates the number of exposures necessary to derive reliable results has been greatly reduced.

An ingenious scheme for measuring parallaxes of a large number of stars was outlined by Kapteyn in 1889 at the conference of the "Carte du Ciel"; it was put into practice by Kapteyn and Donner and the first results were published in 1900. The plan is extremely simple in theory: on the same plate three exposures are made at the epoch of maximum parallactic displacements; half a year later, at the minimum, six other exposures are made on the same plate, and three again at the following maximum. Every star will after development show twelve images; in practice they are arranged as follows:



The distances *a* and *b* are then measured and reduced by a simple process; they yield the parallax of every star visible on the plates with respect to the mean parallax of all the stars measured.

The masterly discussion of the first three plates taken of the region of B. D. + 35° 4013 was published as No. 1 of the *Publications of the Astronomical Laboratory at Groningen.* It brought to light the following points:

1. The accuracy of a parallax to be obtained from one plate with 12 exposures is p.e. = 0″.035, and from three plates 0″.020, when the plates are secured with the instruments used in making the "Carte photographique du Ciel" (focal length = 11.2 feet).

2. There is no serious trouble to be feared from any distortion of the film between the epochs of the different exposures.

3. The results are liable to be vitiated by a "magnitude error," especially when the morning and evening exposures are taken at greatly different hour-angles; most of this "hour-angle error" can, however, be evaded by taking all the exposures in the meridian or at least at the same hour-angle.

Notwithstanding these favorable results, Kapteyn's proposal for a photographic survey of the sky by which the parallaxes of about 800,000 stars brighter than the 10th magnitude would be ascertained, is still in abeyance; even for the regions included in Kapteyn's *Plan of Selected Areas* very few fields have been measured for parallaxes.

In deriving photographic parallaxes of individual stars most of the later observers, using instruments of considerably longer focal length, have discarded the plan of taking exposures of more than one epoch on the same plate. Only the Greenwich observers take exposures for two successive epochs on one plate before it is developed. The difficulties in preserving the undeveloped plates in good condition, the liability of using at one of the epochs a plate for a wrong field or in a wrong position, the possibility of losing several exposures of an earlier epoch by poor observing conditions during a later one, and finally the trouble in placing the plates in exactly the required position at each successive epoch have been the reasons why most observers prefer to have on one plate only the exposures made on a single night.

Kapteyn's evidence for the existence of an "hour-angle error" has prompted the later observers to take, as a rule, all exposures within an hour of the meridian, even when they must thereby restrict observations to times when the parallax factors do not have their maximum values, especially for observatories situated in high latitudes. In addition, the Greenwich and Mount Wilson exposures have been measured in pairs in such a way that the difference in hour-angle of the morning and evening exposures is extremely small. These two observatories have also made somewhat longer exposures in order to be able to use fainter comparison stars, thus making more comparison stars available which at the same time are situated nearer to the parallax-star than is usually the case. It is probably due to a combination of such precautions that these observatories have been able to derive parallaxes with relatively small probable errors.

But even when the effect of a possible "hour-angle error" is avoided, the results may suffer from a "magnitude error" due to inefficient guiding; for this reason it was necessary to devise means of artificially diminishing the apparent magnitude of the parallax-star when it is bright, in order that on the plates it may appear of the same magnitude as the comparison stars.

Hinks and Russell at Cambridge, England, in making their series of parallaxes, begun in 1903, introduced a small color-screen in front of the plate in order to reduce the bright stars; Schlesinger, on the other hand, used in the series of parallaxes started with the 40-inch Yerkes refractor in 1903, a rotating sector in front of the plate; the opening of the sector can be varied so as to make the principal star appear to be of the same magnitude as the mean of the comparison stars. This last device is now in regular use at the Allegheny, Dearborn, Greenwich, McCormick, Mount Wilson, Sproul and Yerkes observatories. Many of the instruments used are visual refractors; in order to improve the quality of the star-images a yellow color-screen is ordinarily inserted just in front of the photographic plate.

The size of the probable errors has considerably decreased with the increase of the focal length of the instruments employed. For the observatories named above it is now smaller than 0″.010 with 45 exposures or less, and in the Mount Wilson parallaxes, where the focal length is 80 feet, it is even smaller than 0″.006 with 16 exposures.

The smallness of the probable errors, however, is not the only thing to be aimed at; far more important and at the same time far more difficult is the avoidance of a systematic error in the resulting parallaxes. These errors can be found by comparing the parallaxes of the same stars as derived by several observers; material for such a discussion, however, would mean an enormous amount of duplication in parallax work.

Another method which seems efficient, is a comparison of the directly determined parallaxes with those derived by some other process, for instance, Adams's spectroscopically determined parallaxes; or they may be compared with tables giving the mean parallax of stars of a certain magnitude, proper motion and spectral type. Tables like these, derived from directly determined parallaxes and from parallactic motions, have been published by Kapteyn and later by van Rhijn. When the parallax material becomes greater such comparisons will show in how far the spectroscopic parallaxes or these tables agree with the results of the directly determined parallaxes; in case of a divergence they will make it possible to investigate the deficiency of either source; moreover, they will show the systematic differences in the results of different observers. A comparison with the tables is only practical for the stars of smaller parallaxes, as a few abnormally large values may make the mean parallax of a certain class of stars illusory. On the other hand, for stars of very large parallaxes a systematic error, if not too great, is less important for any conclusions to be derived.

As an example of such a comparison may be given the results found in this way for the Mount Wilson parallaxes (*Mt. Wilson Contr., No. 136, page 38*); comparing the parallaxes of the 42 stars of magnitudes 5 to 7, spectrum F, G or K, and proper motion less than 0″.500, with those derived from van Rhijn's table, we find $\Pi_{vR} - \Pi_{vM} = -0''.0056$. There are 86 observations of stars of the same class by other observers; the mean of these 86 differences is $-0''.0064$, which is therefore in good agreement with $\Pi_{vR} - \Pi_{vM}$. The material now available does not justify a decision as to the source of difference of all these directly observed parallaxes from van Rhijn's tables, but more material will undoubtedly settle the question as to where such divergences arise. The number of known parallaxes is indeed increasing rapidly. In a list, which is practically complete up to 1918, we find no less than 1273 parallax determinations, many of which are for the same stars; but allowing for the duplication the number of stars with determined parallaxes is more than 800. When we compare this number with corresponding figures already published, we can easily see the rapid increase in this line of work, as shown in the following table:

Author	Source	Year	No. of Parallaxes
Houzeau	Vademecum de l'Astronomie.............	1882	34
Pritchard	Oxford Publ. No. IV.....................	1892	87
Kapteyn	Groningen Publ. No. 24.................	1910	365
Walkey	B. A. A. April 1917......................	1917	625

When from the progress shown in the table we are inclined to be optimistic as to our future knowledge of the distances of the stars, we should keep in mind that for the determination of the parallaxes of the more distant objects we will undoubtedly have to resort to other means than the kind of parallax work discussed here. Yet there is still a great deal to be done and the methods are certainly likely to be considerably improved before we have reached the final limit of accuracy that can be obtained.

Pasadena, January 1918.